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DOE/CS/30438--T1

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Solar Energy Hot Water Heating
and Electric Utilities
A Model Validation

FINAL REPORT

October, 1981

DOE/CS/30438--T1

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DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

I.	Introduction -----	1
A.	Statement of <u>Problem</u> -----	1
	1. Economic impacts of DSHW systems on utilities	
	2. Prediction of electric consumption	
	a. Models can predict consumption	
	b. Use of aggregate system gives aggregate output	
	c. Simulation model better able to adapt to technological change	
B.	Description of TRNSYS Based Model -----	2
	1. Designed for residential solar systems	
	2. Validation by Lin & Fanney	
	3. Component structure	
	4. Aggregate TRNSYS model	
C.	Information Requirements for Study -----	3
	1. DSHW system parameters	
	a. Hardware parameters	
	b. Operating parameters	
	2. DSHW system operating data	
	a. Weather	
	b. Hot water load	
	c. Electric consumption	
II.	Data Collection -----	5
A.	Participant Selection -----	5
	1. Energy grant list	
	2. Initial phone contact	
	3. Site visit	

B.	DSHW System Parameter Collection -----	6
1.	Households	
2.	Manufacturers	
C.	DSHW System Operating Data Collection-----	6
1.	Instrumentation on site	
a.	Recorders	
i.	description - record format	
ii.	operation - tapes, setting, etc.	
b.	Sensors	
i.	description	
c.	Installation	
d.	System characteristics	
2.	Solar data	
a.	Format	
b.	Interpolation to half-hours	
III.	Data Reduction -----	9
A.	Primary Data Translation-----	9
1.	Resulting format	
2.	Problems -	
a.	Missing intervals, 15 min. format	
B.	Secondary Data Translation-----	10
1.	Resulting format	
C.	Input Data Error Analysis-----	10
1.	Introduction	
a.	Use of sensitivity analysis for all but obvious problems	
2.	Instrumentation failures	
3.	Cartridge translation errors	

a.	Description	
b.	Statistical analysis	
4.	Cartridge translation error correction	
a.	Electric and water load data	
i.	correction success from LM period	
b.	Air & water temperature data	
D.	Solar Data-----	14
1.	Catenation with site data	
E.	Aggregation of Data-----	14
1.	Over cluster sites	
2.	Over a time period	
IV.	TRNSYS Modeling-----	14
A.	Reduction of DSHW Systems to Models-----	14
1.	Study constraints	
2.	Division of system into subsystems	
3.	Physical vs. functional components	
4.	DSHW subsystems	
B.	Characteristics of DSHW Systems in Study-----	17
1.	Subsystems similarities	
2.	Functional models in study	
3.	Breakdown of DSHW systems by model	
V.	Model Results-----	18
A.	Measures of Simulation Success-----	18
1.	Total electric consumption	
2.	NRSSE	

B. Modeling Considerations-----	20
1. Aggregation	
2. Load management	
C. System Results-----	21
1. Data groupings used	
2. Base run vs. optimized run	
3. Energy flows	
4. Model success	
VI. Model Sensitivity Analysis-----	29
A. Input Parameters	
B. Input Data	
VIII. Conclusions-----	34
A. Feasibility of Aggregate DSHW System Modeling	
1. Aggregate consumption	
2. Load curve shape	

Introduction

A. Statement of Problem

The solar-electric utility interface study is an investigation of techniques to predict the impact of solar technologies on electric utilities and their customers. Traditionally, the cost effectiveness of solar space and water heating systems has been approached from the perspective of consumer economics. However, as utilities have begun to press for solar electric backup rates, initiating some controversy in the process, the question of solar economics has expanded to include the utility.

The rationale on the utilities part for special solar rates is a belief in high coincidence of solar electric backup consumption with present utility peak load periods. As penetration of the heating market by solar systems occurs such coincidence would impact the utilities load factor and substantially affect their financial picture. To evaluate the effects of solar systems on utility load curves, a model capable of predicting electric backup consumption is required.

A model, useful in predicting solar electric consumption on the scale of a utility, must have several characteristics. First, it should be capable of predicting aggregate consumption of many households such as a utility would observe. These predictions should be on a time scale comparable to existing utility peak duration. The model should be capable of predicting future consumption based on technological and market changes. Finally, the model should be readily available to and runnable by the utility, requiring a minimum of input data. The balance of this report will first describe a model that meets these characteristics and then present a validation of this model, performed using a group of domestic solar hot water systems (DSHW) in the metropolitan Philadelphia area.

B. Description of TRNSYS Based Model

The solar electric backup demand model is based on TRNSYS,

TRNSYS is a residential solar simulation program developed by the University of Wisconsin Solar Lab. It is designed to provide detailed simulations of individual solar systems composed of almost any presently used residential solar technology. The modelers have chosen a component structure whereby each type of component, solar collector, pump, tank, etc., is basically a FORTRAN subroutine. A model of a particular solar system is formulated by linking together the subroutine analogs of the physical system.

Each model subroutine consists of deterministic algebraic and differential equations describing the various flows and levels in the particular component. During a run of the model each component is called in turn. When called, the component computes new outputs, based on the current inputs. The new outputs of the currently executing subroutine then become the inputs to subsequent components.

TRNSYS has been validated by Lin & Fanney* on a single system basis.

To use TRNSYS for predictions of aggregate electric backup consumption, an aggregate solar system is formulated based on average characteristics of a solar system in the utility service area. Aggregate demand and weather data are used as inputs, and aggregate electric consumption is the output. The time between TRNSYS outputs is adjustable by the modeler, and typically is of the order of the input data time step. Thus by obtaining 30 minute increment input data, an output level can be obtained every 30 minutes.

Finally, the data used to construct and run the models are available through market surveys, weather records and hot water consumption pattern data.

*S.T. Lin and A.H. Fanney, Comparing Experimental and Computer Predicted Performance on Solar Hot Water Systems, ASHRAE Journal, May, 1980, p. 34.

C. Information Requirements for Validation

To determine whether the previously described model can indeed predict aggregate electric demand requires testing or validation of the model. This can be done by gathering the input data for the model, running the model using the input data, and then comparing the output of the model with the real world.

More specifically, for a domestic solar hot water (DSHW) system, physical parameters of the system such as collector area would be gathered for a group of systems. Weather data, hot water demand and system electric consumption would be recorded for this group over a period of time. The system parameters would be used to define an aggregate model. The averaged hot water demand and weather would constitute the inputs to the model. Then the modeled aggregate electric consumption would be compared with the observed aggregate electric consumption.

As already indicated, two types of information are required for the validation; parameters of a set of DSHW systems, and input and output data on the same set of systems. The parameter list obtained for systems used in this study is shown in Table 1. For the most part, these figures can be obtained using the questionnaire sent to the system owner and the appropriate manufacturers. This satisfies one of the usability constraints that the parameter data be obtained by a utility. This is important, as utilization of this demand model by a utility will only be practical if the data is easily obtainable.

Starred parameters indicate information required by the TRNSYS model that is not readily available from either the homeowner or manufacturer, notably pumping rate. However, it will be shown that these parameters can be estimated with satisfactory accuracy.

Input Parameters

Collector Parameters

area
efficiency curve
orientation
tilt

Pump Controller

upper dead band
lower dead band

Pump

flowrate*

Tank

volume
dimensions
insulation
heating elements size & location

Data Input

Electric Consumption
Hot Water Consumption
Ambient Air Temperature
Cold Water Inlet Temperature
Solar Insolation

Table 1

The other type of information required to validate the demand model is input and output data; all the time-varying quantities entering or leaving the system. They are also listed in Table 1. Total electric and hot water consumption were recorded at half hour intervals on all the systems. Average ambient air temperature at the collector and inlet water temperature were recorded on most of the systems at half hour intervals. Total solar radiation on a southwest tilted surface was collected at one hour intervals at a central site.

II. Data Collection

A. Participant Selection

In the study locale, metropolitan Philadelphia, the number of domestic solar space heating systems is quite small. Because of this, domestic solar hot water (DSHW) systems were used to perform the study.

The initial list of local DSHW systems was obtained from the Governor's Energy Council in the form of a list of solar grant recipients. The selection process for study participants was conducted in two phases. DSHW system owners were first contacted by phone to determine if their system had electric backup and if they were willing to participate in the study. Then phone qualified sites were visited to determine if there would be any problem with instrumentation. Three clusters of participants were used. At each, the installation of equipment was accomplished, data was collected for at least four weeks, the equipment was removed, and the

process repeated.

B. DSHW System Parameter Collection

During the site visit, DSHW system site parameters were collected.

These consisted of all site specific features of the system, such as collector tilt and compass orientation, type of systems, working fluid, etc. Wherever possible, parameters were measured, i.e. hot water set point was taken with a thermometer.

Other system parameters, such as collector performance and tank insulation were obtained by contacting the system manufacturers.

C. DSHW System Operating Data Collection

On the second visit to study participants, site instrumentation for operating data was installed. Site instrumentation was based on Westinghouse W31-A magnetic tape event recorders, that had been modified for battery operation in instances of power failure. Sensor systems for temperature, water consumption and electric consumption were designed to interface with these recorders. The W31-A is a two-channel recorder with one channel for timing information and one channel for data. The recording format is the simplest possible type; pulses spaced along the magnetic tape in an event format. Pulse height and spacing carry no information. At one-half hour intervals, a pulse is placed on the time channel. The information obtained from the data channel is simply the number of pulses on the data channel between one-half hour time pulses.

To make a data recording, a rewound, erased tape cartridge is inserted into the recorder. The time clock of the recorder is set and the time marked on the cartridge. In the case of electric and water flow data, the current meter readings are also recorded on the cartridge. When the data cartridge is removed, time and consumption data is again recorded on the cartridge. Normally a test

tape is run for an initial week and translated to determine that the system is operating properly.

Two types of sensor systems were used to interface with the recorders, one for consumption and one for temperature data. The consumption interface consisted of a total consumption meter, with a pulse initiator for every unit of consumption. The pulse initiator was simply wired to the recorder input. Each pulse on the tape then corresponded to a unit consumption of electricity or water.

The temperature interface was slightly more complex, consisting of a resistive temperature device (RTD), a bridge circuit and a voltage-to-frequency converter. The RTD's resistance is proportional to its temperature. The resistance of the RTD was converted to a voltage by the bridge circuit. Finally the voltage was converted to a pulse train by the voltage-to-frequency converter. The number of pulses in a given time interval is proportional to the temperature of the RTD. Again this pulse train was simply wired to the input of the recorder.

This recording system has several advantages. The components are relatively simple and rugged. The high voltage levels, DC nature of the RTD, and pulse nature of the recorder give high noise immunity. The summation of the pulse train in the translation process has the effect of averaging the data over a half hour interval, which is the form of data required to run the TRNSYS simulation. The timing pulses make the system insensitive to absolute tape speed.

However the system also has several disadvantages. There are no absolute time marks on the tape, only 30 minute intervals. Thus documentation of the time period covered by each tape, and comparison of two tape periods depends upon hand marking of the tape start and stop times. It is difficult to check the calibration of the equipment on site, except in a crude way by counting pulses. The data format is awkward in that the data requires two translation steps before it is in a form compatible with simulation model requirements.

Figure 1 illustrates a typical DSHW system with the location of the various

Typical DSHW system with sensor locations

Figure 1

sensors. The RTD sensor to measure ambient air temperature was mounted behind the collector panel whenever possible. When the collector was mounted flat against the roof, the sensor was placed in a shaded area as close to the collector as possible. The water temperature sensor was placed on the cold water inlet pipe, where the water mains entered the basement if the system used distributed water, or on the water tank if it was well water.

The water meter was placed in the most convenient place in the systems water line, unless it was a drain down system. Then if possible, the meter was placed after the preheat tank, to avoid measuring water lost during drain down. The electric meter was installed so as to measure only electricity used to heat water. Power for system pumps was not included.

After installation, hot water temperature, cold water temperature and ambient air temperature were recorded.

Solar data for the study was obtained from the National Solar Data Network (NSDN). The form of the data was total radiation on a 50° tilted surface facing south. The measurement site was West Chester, a town about 10 miles west of Philadelphia. As there is no abrupt change in terrain between the two locales, i.e. mountains, this data should match the insolation that was present at the individual sites. Insolation readings are on an hourly instead of half hourly basis, requiring interpolation to generate the additional increments.

III. Data Reduction

A. Primary Data Translation

The purpose of the primary data translation is to obtain the information from the Westinghouse recorder cartridges and put it in a form readable by a computer, in this case an IBM 370. The data from each cartridge was placed in a standard format with space for one year of data. The position of the data in the file indicates the time base of the data, i.e. the first piece of data

corresponds to the first half hour of the year. The last piece of data corresponds to the last half hour of the year. Thus since the data strings in this study were only four to six weeks long, most of the data file for each variable was blank.

B. Secondary Data Translation

The purpose of the secondary translation was to put the data in a TRNSYS compatible form. This involved accessing the four separate data files containing each of the site variables, moving to the start of the data, and reading the four variables to a new file.

C. Input Data Error Analysis

The purpose of this section is to discuss problems with the input data. An error analysis will be presented in the form of a sensitivity study in a later section. This section is presented separately as the type of errors presented here would, if not corrected, render the input data useless for the model.

Two classes of errors will be discussed. The first class of error was due to some type of failure in the sensor-recorder system. Since each variable had its own data collection system, failure would only effect one of the four variables being recorded. If the failure was of a temperature variable, the data was kept as the temperature data was felt to be of secondary importance. And, since the data is combined with other sites in the aggregated form, the other sites' temperature data is in effect substituted for the missing data. When the failure was an electric or water flow variable however, the site was not used. Three sites had either electric or water flow failures and were deleted from the study.

The second class of error originated in the cartridge translation process and affected virtually all of the study data. The error consisted of the

translation equipment occasionally using a 45 minute interval instead of a 30 minute one. The interval lengthening has two effects, placing 50% more pulse counts in an interval than should be there, and destroying the time base of the data. The second effect was the more serious one, as all the data following a lengthened interval was shifted by 15 minutes. The average data string was shortened by about 10% due to this effect.

This type of error was clearly visible in the temperature data, as it caused sudden jumps in the temperature variable. This fact was used to locate and correct the interval errors in the temperature data. Figures 2a and b are histograms of the distance between interval errors for two temperature data strings.

Unfortunately, the interval errors in the electric and water flow data strings could not be detected as sudden jumps were in the original data. Many of the intervals also have zero consumption, and since 150% of zero is still zero, it is not possible to determine an interval error from a normal interval. Because of this, the only correction possible was to simply add the number of missing intervals (each interval error caused the loss of 1/2 interval) evenly along the length of the data string. If the original interval errors were evenly distributed throughout the data, as indicated in 2a; this will correct the problem. If the interval errors are skewed however, as illustrated in 2b, then the data points will still be shifted in time from their correct position over most of the string.

It should be emphasized that the histograms of Figure 2 are based on temperature data and not electric or water flow. However, as the translation equipment would not be able to distinguish between the two types of data, it is safe to assume that the interval errors would be distributed in a similar manner throughout the data. Study of the temperature data yielded no discernible pattern in regards to error distribution. Some of the histograms indicated

Histograms of Errors in Input Data

Frequency

Each * Equals 3 Points

120	*
117	*
114	*
111	*
108	*
105	*
102	*
99	*
96	*
93	* *
90	* *
87	* *
84	* *
81	* *
78	* *
75	* *
72	* *
69	* *
66	* *
63	* *
60	* *
57	* *
54	* *
51	* *
48	* *
45	* *
42	* *
39	* *
36	* *
33	* *
30	* *
27	* *
24	* *
21	* *
18	* *
15	* *
12	* *
9	* *
6	* * *
3	* * *

Interval	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Class	Lower Bound 0. Upper Bound 36.																			
Mean Intrvl & Stand. Dev.																				
	3.808		1.258																	

Figure 2a

Histograms of Errors in Input Data

Frequency

Interval 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
 Class Lower Bound 0. Upper Bound 36.

Mean Intrvl & Stand. Dev.
 8.453 5.747

Figure 2b

very even distributions and others quite skewed distributions. There did not appear to be any correlation of the distributions at any one site.

D. Solar Data

As already indicated, the solar data was not measured during the study, but obtained from the NSDN. The only modification to the data was to interpolate half hour values from the average of the hourly ones. The solar data was then added to the other four variables in each of the customer files, taking care to properly align the dates and times.

E. Aggregation of Data

The raw customer files were not used to run TRNSYS simulations, but were always aggregated together. This was accomplished in two steps. First, the data strings would be averaged together over sites, with, for example, five Monday noon readings averaged together, five Monday 12:30 readings averaged together, and so on. During this process it is necessary to indicate to the program the relative starting time of each of the five sites so that the times are properly aligned.

The second stage of aggregation is to collapse the month-long data string into one only 24 hours long. Actually two sets of data are generated in this process, as weekend days are kept separate from weekdays.

The process proceeds similarly to the first aggregation, except all noon weekday readings are averaged together, then all 12:30 readings, all 1:00 readings, and so on for 24 hours.

IV. TRNSYS Modeling

A. ~~Reduction of DSHWS Systems to Models~~

TRNSYS approaches DSHW modeling by reducing the system to its component subsystems, and then representing these subsystems by algebraic and differential equations. A simple example is a pump. The pump has three inputs: temperature of incoming fluid, mass of incoming fluid, and a control input indicating whether the pump is on or off. There are two outputs: fluid temperature and mass. The equations are:

$$T_{out} = T_{in} \quad M_{out} = \gamma \cdot R \quad M_{in} = \gamma \cdot R$$

Where

γ = control function

R = pumping rate

T = temperature

M = mass

$T_{out} = T_{in}$

$M_{out} = \gamma \cdot R$

$M_{in} = \gamma \cdot R$

The pumping rate R, is a parameter of the pump set at the beginning of the simulation and held constant throughout. The other components in a DSHW system are represented in a similar, though somewhat more complex way. By linking together the component submodels, a model of the entire DSHW system is generated. Different systems are modeled by linking different components submodels.

However, the functional as opposed to physical variations of the subsystems determine the submodel variations that must be used to simulate the DSHW systems. Thus even though two subsystems are physically quite different, if they perform similar functions, they can be modeled in similar ways. For example DSHW systems with external heat exchangers are intended to

produce water tanks with temperature stratification. Drain down systems can produce the same effect without heat exchangers. The physical differences between the two systems are substantial, but the results are quite similar in terms of the water temperatures in the tanks.

Thus, in terms of building TRNSYS models, all DSHW systems with similar functional subsystems can be treated as the same model. Only subsystem parameters must be varied to create individual simulations of these DSHW systems. However, rather than running simulations of each variation of the basic models, an aggregate model can be formed by averaging the parameters of the different DSHW systems.

Having established that it is only necessary to vary a TRNSYS model when there is a functional variation in a DSHW system, these functional variations will be explicitly explored. Analysis of DSHW systems reveals that there are four principal functions the system must perform:

- collection of solar energy and transformation into heat
- transfer of heat to water in storage tank
- storage of heated water
- additional heating of water as required

~~These four functions are performed by five subsystems:~~

- solar collectors
- pipes, pumps and heat exchangers
- heating elements and thermostats
- system controllers
- storage tanks

To formulate the simulation models, the variation among these five subsystems will have to be determined for each of the individual systems in the study.

B. Characteristics of DSHW Systems in the Study

With five discrete parts to a DSHW System, even with only two alternatives per subsystem, there are 32 possible combinations of DSHW systems. However, upon examining the systems in the study, the number of alternatives were greatly reduced.

First, since simple aggregate systems were desired, a coarse level of system differentiation was established. Details such as length of pipe run to collectors, pipe insulation, interior vs. exterior pipe runs, height of collector above tanks, pipe diameter, etc. were ignored.

Second, except for parameter variations, all collectors and system controllers were virtually identical. Also, heaters and thermostats were identical except that one tank systems only possessed one heater while two tank systems always had two heaters.

Third, the various heat exchangers and drain down configurations could all be divided into two classes, those that stratified a storage tank and those that did not. No detailed information was available concerning the characteristics of the heat exchangers on observed systems.

Fourth, in two tank systems, the second tank always had the same configuration, one heater near the top of the tank, and one near the bottom.

Fifth, in one tank systems, the heater and collector piping was always arranged to establish some stratification in the tank.

Based on these qualifications Table 2 lists the possible simulation models for the DSHW system in the study.

Table 2

Single tank, 1 heater, stratified

Double tank, 2 heaters, first tank stratified

Double tank, 2 heaters, first tank unstratified

One additional variable differentiating approximately half of the DSHW systems in the study was the presence of load management on the electric heating auxiliary. PECO has two load management cycles, one cycle from 4 P.M. to 10:30 P.M., and the other from 4 P.M. to 9 P.M. and from 10:30 P.M. to midnight. During this period, load managed (LM) systems could consume no power. But during the rest of the day they behaved as non-load managed (NLM) systems.

Table 3 gives a breakdown of the observed systems by the three types listed above. Several other pieces of information are also included in the table, LM vs NLM; starting date of measurement; whether instrumentation failed; and the water heater set point. Of 18 instrumented sites, acceptable data was obtained from 13.

V. Model Results

A. Measures of Simulation Success

Two measures of simulation success have been developed to quantitatively compare model with observed DSHW system performance. These are total electric consumption over a 24 hour period and normalized root sum of squares error of the simulation from the observed electric consumption. Total simulated electric consumption and total observed electric consumption are outputted from the model at 24 hour intervals. These values are tabulated for the different simulation runs.

Table 3

Breakdown of Observed Systems by Functional Type

Cluster #	Stratified/1 Tank					Stratified/2 Tank					Unstratified/2 Tank				
	#	LM/NLM	Date	S.P.	Data	#	LM/NLM	Date	S.P.	Data	#	LM/NLM	Date	S.P.	Data
1	11	LM	12/2	133		12	LM	11/4	132						
	14	NLM	11/21	110		13	NLM	11/20	131						
						15	LM	12/11	114						
						16*	NLM	12/12	149	ND					
2	21	LM	1/12	119		23	NLM	1/13	122		22	LM	1/9	124	
	24	NLM	1/11	116		26*	NLM	1/26	149	ND					
	25	LM	1/22	138	ND										
3	36	LM	3/10	120		33	LM	3/17	116		31				ND
	37	NLM	3/13	128		35	NLM	3/2	120	ND	32	NLM	3/4	120	
											34	LM	3/16	125	ND

LM = Load Managed

S.P. = Hot Water Set Point Temperature

NLM = Nonload Managed

ND = No or Bad Data and Not Used in Study

*

Same site used twice, electric recorder failed.

The normalized root sum of square errors is given by:

$$\text{NRSSE} = \frac{\sum_{i=1}^N (\text{Obs. elec.}_i - \text{Sim. Elec.}_i)^2}{N \sum_{i=1}^N \text{Obs. elec.}}$$

where N = number of half hour intervals over which the comparison is made.

NRSSE measures the goodness-of-fit between the simulated and observed electric consumption curves. It is evaluated at half hour intervals over the period of comparison.

B. Modeling Considerations

Before discussing the results of individual systems, some overall considerations will be mentioned. As discussed earlier, data was aggregated in two stages, first by site and then over time. While runs can be performed at either stage of aggregation, satisfactory results were only obtained with data collapsed to 24 hour periods. The poor results at the first level of aggregation were probably due to the random shifts in the time of the data caused by the translation error. As corresponding half hour electric and water flow data points are randomly shifted relative to each other and the rest of the input data, shifting of the simulated consumption relative to the observed consumption is to be expected. However averaging together enough data tends to eliminate the random elements, leaving the underlying pattern.

A second data consideration is due to load management. PECO has indicated that the load management periods is in the last eight hours of the day, from 4 P.M. until midnight. However LM control did not seem to be consistent from one LM system to another based on the observed electric consumption. In a few cases, the LM period corresponded to that indicated,

in other cases the LM period was shifted or was shorter than indicated, and in some cases no LM period was apparent at all. Whether this is due to problems with the LM clocks at the sites, the shifting in the data due to the translation errors, or a combination of both is not known.

To deal with this problem, the NRSSE measure is only evaluated from midnight to 4 P.M., eliminating most of the variability associated with the LM effects. Since this model will be useful mainly to those interested in the uncontrolled consumption of auxiliary electricity, ignoring LM does not seem to be a serious limitation. Further, TRNSYS is capable of modeling the LM effect, but it is necessary to have the LM period more accurately defined than indicated by our data.

C. System Results

The results of running the 1-Tank and 2-Tank stratified models are described in Tables 4 and 5. Results for the 2-Tank unstratified models will be discussed shortly. The two tables are arranged to represent output from the models for various input data sets. For each model, the data sets comprised data taken from DSHW systems of that model type, as well as data sets made up from data taken from all the DSHW systems in the study. The second data set used to provide a basis of comparing the two models.

Each data base was further subdivided into one or two groups. The first column of the tables describes the particular portion of the data set used to obtain the results in the rest of the columns. "All" represents use of all the site data of the category. "LM" represents use of data from load managed sites. "NLM" represents use of data from non-load-managed sites.

The rest of the information in the first column describes the other input variation, the loss parameter for the storage tanks. Each set of data was run through the respective model in two different modes. First a base

Data From 1 Tank Systems

Portion of Data Base	Observed Electric	Simulated Electric	Tank Losses	Energy To Hot Water	Sim/Obs.	NRSSE	Sim. Solar Fraction	Obs. Solar Fraction	# Data Pts.
Base R = 6	3.36×10^4	1.99×10^4	$.566 \times 10^4$	4.07×10^4	.591	.521	.572	.438	170
All Optim. R = 1.4	3.36×10^4	3.37×10^4	2.24×10^4	4.03×10^4	1.002	.212	.461	.461	
Base R = 6	2.67×10^4	1.82×10^4	$.592 \times 10^4$	3.16×10^4	.681	.521	.516	.417	68
LM Optim R = 2	2.67×10^4	2.68×10^4	1.67×10^4	3.14×10^4	1.006	.299	.444	.443	
Base R = 6	3.83×10^4	2.21×10^4	$.529 \times 10^4$	4.66×10^4	.577	.460	.573	.436	101
NLM Optim R = 1.1	3.83×10^4	3.86×10^4	2.54×10^4	4.60×10^4	1.008	.224	.458	.458	

Data From All Systems

Base R = 6	4.22×10^4	2.40×10^4	$.588 \times 10^4$	4.88×10^4	.568	.462	.561	.419	393
All Optim R = 1.2	4.22×10^4	4.21×10^4	2.80×10^4	4.74×10^4	.998	.186	.441	.440	
Base R = 6	4.39×10^4	2.86×10^4	$.556 \times 10^4$	5.54×10^4	.652	.398	.533	.424	200
NLM Optim R = 1.3	4.39×10^4	4.40×10^4	2.36×10^4	5.48×10^4	1.002	.216	.439	.438	

Results for One Tank Model

Table 4

Data From 2 Tank Systems

Portion of Data Base	Observed Electric kj/24hr	Simulated Electric kj/24hr	Tank Losses kj/24hr	Energy to Hot Water kj/24hr	Sim/Obs.	NRSSE	Sim. Solar Fraction	Obs. Solar Fraction	# of Data Pts.
Base R = 6	3.44×10^4	2.27×10^4	1.40×10^4	3.68×10^4	.660	.427	.549	.449	144
All Optim R = 3	3.44×10^4	3.45×10^4	2.69×10^4	3.66×10^4	1.003	.291	.458	.459	
Base R = 6	3.14×10^4	1.87×10^4	1.42×10^4	3.23×10^4	.595	.546	.599	.473	89
LM Optim R = 2.8	3.14×10^4	3.15×10^4	2.92×10^4	3.19×10^4	1.003	.353	.486	.486	
Base R = 6	3.94×10^4	3.16×10^4	1.34×10^4	4.70×10^4	.800	.346	.478	.423	54
NLM Optim R = 3	3.94×10^4	3.96×10^4	2.24×10^4	4.37×10^4	1.005	.286	.426	.426	

Data From All Systems

Base R = 6	4.22×10^4	2.89×10^4	1.33×10^4	4.94×10^4	.684	.349	.541	.447	393
All Optim R = 3	4.22×10^4	4.02×10^4	2.58×10^4	4.93×10^4	.953	.139	.463	.453	
Base R = 6	4.39×10^4	3.31×10^4	1.27×10^4	5.62×10^4	.755	.282	.520	.449	200
NLM Optim R = 3	4.39×10^4	4.32×10^4	2.38×10^4	5.60×10^4	.984	.146	.460	.455	

Results from 2 Tank Model

Table 5

model was run using a particular data set, with model parameters derived from the average characteristics of the DSHW Systems from which the data was taken. After obtaining results for the base case, the model was rerun adjusting the tank loss parameter until the total simulated electric consumption matched the total observed electric consumption.

This procedure is used for two reasons. First, as the model was intentionally kept simple, both to facilitate its use and to realistically represent the type of data available to a utility, heat losses due to pipes, heat exchangers, etc. are not accounted for. Total system heat losses are thus underestimated by the system. Matching the simulated consumption to the observed gives a good indication of what the actual total losses must be, or alternatively yields an effective system loss coefficient.

The second reason for this procedure is to investigate the improvement in the simulated to observed time of day use pattern. The time of day consumption pattern is the most important information that the model can yield. If a utility has some information on total DSHW electric consumption, (based on separate water heating metering) this additional data could be used to improve the time of day predictions.

The results of the above mentioned variations and other data related trends are tabulated in the remaining nine columns of the table. The next four columns list values of total energy consumption in KJ for the 24 hour period simulation. Observed and simulated electric are, of course, the observed aggregate electric consumption of the DSHW systems and the simulated aggregate consumption respectively. Tank losses refer to the energy lost to the environment from the hot water tanks as predicted by the simulation. Finally, Energy to Hot Water refers to the simulated flow of energy to the water passing through the heating system. It is a function of the water flow,

the inlet water temperature, and the outlet (hot water) temperature.

The next four columns list various derived statistics. Sim/Obs is just the ratio of simulated to observed electric consumption. NRSSE is the normalized root sum of squares error. These two statistics are the figures of merit discussed in the previous section. Figure 3, parts a, b and c, illustrates the correspondence between the NRSSE value and the similarity between the observed and simulated electric consumption. In each plot, the 1's indicate observed electric consumption, the 2's simulated consumption, and the 3's observed water consumption. All the curves are from runs of the 2-Tank model.

Curve A uses the data set obtained from LM 2 tank systems. The model has not been optimized for DSHW system heat losses and the NRSSE value is .546. Curve B uses the same input data as curve A, but the tank loss coefficients have been adjusted so that the total simulated electric consumption matches the observed. The NRSSE value has improved to .353. Finally curve C shows the results when data obtained from all the observed systems was used as input and the model was optimized for losses. Here the NRSSE is best at .139.

The next two columns show simulated and observed solar fractions. They are computed from the equation:

$$\text{Solar fraction} = \frac{\text{Solar energy into system}}{\text{Solar input} + \text{electric input}}$$

where the electric input is the simulated and observed values respectively.

Finally, # of Data Pts refers to the number of data points averaged together to generate each 30 minute interval in the 24 hour data set.

An unoptimize simulation result for a LM 2 Tank system

Figure 3A

Same as 3A but optimized

Figure 3B

Optimized simulation using all of observed systems.

Figure 3C

This section concludes by mentioning the simulation of the Unstratified 2-Tank Model. Initial runs were performed to determine if stratification was an important parameter. Runs with and without stratification yield almost identically poor results. However, runs of the other two models showed stratification greatly improved model performance. Because of these results, it was concluded that the data base for the Unstratified 2-Tank Model was too small to enable any conclusion to be obtained. Consequently, no further work was done with this model.

VI. Sensitivity Analysis

A sensitivity analysis of the two DSHW system models was performed to determine the effect of input changes on the electric auxiliary backup consumption. The results are shown in Tables 6 and 7 for the 1 Tank and 2 Tank models respectively. The left side of the tables describes the input changes to each of the respective models. The right side tabulates the model response using two measures: the percent change in electric backup consumption from the base case, and a resulting transfer coefficient. The percent change is calculated from the formula

$$\Delta \% = \frac{(\text{Elec. aux. w/input change}) - (\text{Elec. aux. w/o input change})}{(\text{Elec. aux. w/o input change})}$$

The transfer coefficient is calculated from the formula

$$\frac{\% \text{ change in output}}{\% \text{ change in input}} = \text{transfer coefficient}$$

Thus a transfer coefficient of -0.5 would indicate an output response one-half as large as the input change on a percentage basis and in the opposite direction of the input change.

Input Change		% Change Auxiliary	Trans. Coeff.
Solar Collector	high eff. +16.0%	- 8.7%	- .54
Solar Collector	med. eff. +11.8%	- 5.5%	- .47
Collector Area	+10.0%	- 1.2%	- .12
	-10.0%	+ 4.1%	- .41
Controller upper dead band $8.9^{\circ} \rightarrow 5.0^{\circ}\text{C}$ lower dead band $3.0^{\circ} \rightarrow 1.7^{\circ}\text{C}$		- .1%	.00
Pump Flowrate	100 $\rightarrow$ 50 kg/hr	-11.7%	.23
	100 $\rightarrow$ 200 kg/hr	4.9%	.05
Tank Volume	+25.0%	7.2%	.29
Tank Volume	-12.5%	- 2.1%	.17
Tank Heat Loss	+25.0%	12.8%	.51
	-25.0%	-12.7%	.51
Tank Setpoint	$118^{\circ}\text{F} \rightarrow 128^{\circ}\text{F} + 8.5\%$	23.0%	2.71
	$118^{\circ}\text{F} \rightarrow 108^{\circ}\text{F} - 8.5\%$	-22.7%	2.67
Hot Water Consumption	+10.0%	8.7%	.87
Hot Water Consumption	-10.0%	--7.4%	.74
Solar Insolation	+10.0%	- 6.6%	- .66
Solar Insolation	-10.0%	7.3%	- .73
Ambient Air Temp.	+10.0%	- 4.4%	- .44
Ambient Air Temp.	-10.0%	4.7%	- .47
Cold Water Inlet Temp.	+10.0%	- 2.1%	- .21
	-10.0%	3.2%	- .32

Sensitivity Analysis

1 Tank Model

Input Change		% Change Auxiliary	Trans. Coeff.
High eff. Solar Collector	+ 4.1%	- 1.89%	- .46
Low eff. Solar Collector	-13.9%	+ 6.78%	- .49
Collector Area	+10.0%	- 3.62%	- .36
Collector Area	-10.0%	4.13%	- .41
Controller upper dead band $8.9^{\circ} \rightarrow 5.0^{\circ} \text{C}$ lower dead band $3.0^{\circ} \rightarrow 1.7^{\circ} \text{C}$		- 0.3%	.01
Pump Flowrate	100 50 kg/hr	- 9.3%	.19
	100 200 kg/hr	+ 5.6%	.06
Tank Volume	+25.0%	10.0%	.40
	-12.5%	- 6.6%	.53
Tank heat loss	+25.0%	19.3%	.77
	-25.0%	-20.2%	.81
Tank Setpoint	$127^{\circ} \text{F} \rightarrow 137^{\circ} \text{F}$ +10 $^{\circ} \text{F}$ + 7.9%	21.0%	2.67
	$127^{\circ} \text{F} \rightarrow 117^{\circ} \text{F}$ -10 $^{\circ} \text{F}$ - 7.9%	-18.6%	2.36
Hot Water Consumption	+10.0%	8.3%	.83
	-10.0%	- 8.1%	.81
Solar Insolation	+10.0%	- 6.0%	.60
	-10.0%	5.3%	.53
Ambient Air Temp.	+10.0%	- 3.3%	.33
	-10.0%	1.7%	.17
Cold Water Inlet Temp.	+10.0%	- 2.5%	.25
	-10.0%	+ 2.0%	.20

Sensitivity Analysis

2 Tank Model

The degree to which each input was varied was chosen to represent the larger of two possible factors. These were the largest either the maximum possible error in the reported value, or the greatest variation in the value between the systems observed. For example, the pumping rates were varied from 50 kg/hr, about 13 gal/hr, to 200 kg/hr, about 53 gal/hr as actual rates were not known. But only two sets of controller dead band intervals were observed. 8.9°C and 3.0°C for the upper and lower dead bands respectively were the most common values, but a few systems had 5.0°C and 1.7°C dead bands.

Both the parameters and the half hourly inputs were varied. To preserve the basis form of the input data, half hourly values were all either increased or decreased by the same factor, 10%. The base system used for each model was the optimized NLM system of the results section.

Starting with the solar collection subsystem two parameters were changed: collector area and collector efficiency. The calculation of collector efficiency change was more complex than the other inputs as efficiency is in the form of a curve represented by

$$\eta = \frac{\Delta T}{\text{insolation}}$$

where

η = efficiency

Δ = collector temp. - ambient temp.

insolation = solar insolation

The input efficiency change used was the average efficiency over a 24 hour period. The collector efficiencies represent a high, medium and low case, where the 1 Tank Model base system used the low efficiency model and the 2 Tank Model base system used the medium efficiency mode. The collector area variation

of 10% derived from manufacturers' rating systems. Some rate their collectors on effective area and others on physical area. These typically vary by 10%.

With one exception which was lower, the transfer coefficients for this subsystem were all close to 0.5. This is consistent with the solar fraction calculated for the systems of about 0.5.

The controllers were all very similar except for dead band settings. However use of either setting gave very similar results as expected from the very small transfer coefficient.

The pumping rate also had a rather small transfer coefficient, though of the opposite sign of that expected; decreasing the pumping rate decreased the auxiliary consumption slightly. A slower pumping rate would tend to increase the temperature of the return water from the collector. This in turn would increase heat losses in the pipes and external heat exchangers. However, as this effect was not included in the model, the sensitivity analysis does not include it. Thus in this case the sensitivity analysis is probably giving a false indication.

The storage subsystem is represented next and has some of the most interesting results in the sensitivity analysis. Most important is the hot water temperature setpoint, which has the highest transfer coefficient of any of the inputs, averaging 2.5 for the 2 Tank Model and 2.7 for the 1 Tank Model. This implies a 25 to 27% increase in auxiliary consumption for only a 10% increase in setpoint. The basis for this result is that energy to hot water consumption and environmental losses both increase with increasing setpoint temperature. However, the environmental losses will be somewhat exaggerated by the models, as all system losses are being represented by tank losses. In fact 50% to 67% would be attributable to losses between collector and tank. Correcting for this would reduce the transfer coefficients by a factor of 17% to 22%.

The other interesting feature of the tank subsystem is that the volume and heat loss coefficients are quite different between the 1 and 2 Tank Models. The 2 Tank Model is somewhat more sensitive to changes in tank volume and heat loss coefficient, probably resulting from the input changes being made in two tanks rather than on only one.

The final section of the sensitivity analysis examines the effects of variations in input data. Each half hour value was changed by 10% to investigate the effects of instrumentation errors. The hot water consumption and solar insolation effects were the largest, averaging transfer coefficients of .8 and .6 respectively. This is about 20% higher than would be expected based simply on the fraction of energy out of the system to hot water and the solar fraction of energy into the system.

Finally, the ambient air and cold water inlet temperatures have relatively minor effects, all possessing transfer coefficients of less than 0.5.

VII. Conclusions

At the beginning of this report the major characteristics required by a DSHW load model were described. These basically consisted of:

- 1) a model capable of accurate time of day electric backup predictions for an aggregate group of solar systems and
- 2) a model reasonably usable by the utility in terms of data collection and complexity.

The subsequent data presented here indicates that this model is capable of accurate time of day load predictions. The NRSSE values for optimized systems exhibit remarkably good fit between simulated and observed electric consumption curves. Further the load predictions do not appear to be very sensitive to individual variations in most of the inputs. Rather the output load is the sum of a large number of factors indicating that the model is reasonably robust.

However, to achieve the accurate load predictions cited above it was necessary to include as input, data that was not in the initial formulation of the model, i.e. total electric consumption for a specific period. The total simulated electric consumption was matched to the total observed consumption by adjusting the environmental losses from the DSHW system tanks. Good fits between predicted time of day loads and observed time of day loads were then achieved.

The requirement for optimization just described indicates a problem with the initial model. As originally formulated 50% or more of the DSHW system's environmental heat losses were not being accounted for. These are losses associated with the pipes and heat exchangers used to transfer heat from the collector to the storage tank. The optimization was essentially adjusting the heat losses from the storage tanks to include these extra factors. Thus the original model must be reformulated.

Three possible modifications to the original model that would still leave it reasonably usable by the utility have been devised. The extra loss factor could be included directly by modeling the capacitance and loss effects of the pipes and external heat exchanges. This would require a moderate amount of additional information on pipe diameter, materials, insulation, and lengths and a rather slight addition to the TRNSYS simulation itself in comparison to the original model.

It would also be possible to use the same optimization techniques employed in this work if the information were available. This new information would consist of total electric consumption over some period of time for a set of DSHW systems. The set of systems would be modeled based on parameter information obtained from DSHW system owner and system manufacturers. The model would then be corrected for losses by adjusting the loss parameters until total

predicted consumption matched the observed value. The predicted time of day electric consumption would then accurately reflect the actual. The total electric consumption would be available where submetering of electric hot water heating systems was practiced.

The final technique for modifying the original model would be to assume a heat loss for the DSHW system. From the column of optimized tank losses in the results table, it can be seen that the losses are quite uniform across 3 out of 4 distinct groups. A reasonable estimate of day, winter system losses could be 2.7×10^4 kj. However, as data was only collected during winter and spring months, extrapolation to the rest of the year would be suspect.